

# Anomalous quark-gluon chromomagnetic interaction and high energy $\rho$ -meson electroproduction

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## Abstract

It is shown that existence of a large anomalous chromomagnetic moment of quark induced by non-perturbative structure of QCD leads to the additional contribution to exclusive  $\rho$ -meson electroproduction off proton target. The significant contribution coming from new type of quark-gluon interaction to the  $\rho$ -meson production cross section for both transversal and longitudinal polarization of virtual photon is found. Such non-perturbative contribution together with conventional perturbative two-gluon exchange allows us to describe the experimental data at low  $Q^2$  for transversal polarization. However, in the longitudinal polarization case there is still some discrepancy with the data. The possible source of this deviation is discussed.

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# 1 Introduction

One of salient features of perturbative high-energy QCD is conservation of the  $s$ -channel helicity of quarks. On the other hand, the QCD vacuum possesses a nontrivial topological structure - instantons are an extensively studied example (for the reviews [1, 2]). Such topological fluctuations generates the celebrated multiquark t'Hooft interaction which is responsible, for example, for the solution of  $U_A(1)$  problem in QCD [3]. Additionally, instantons were shown to generate a non-trivial spin-flip, i.e.,  $s$ -channel helicity non-conserving, *quark-gluon interaction* [4]. This interaction can be described in terms of an anomalous chromomagnetic moment of quarks (ACMQ) complementary to the perturbative Dirac coupling. Novel contributions from this non-perturbative interaction to the soft Pomeron, gluon distribution in the nucleon and sizable spin effects in strong interactions have already been discussed in the literature [4, 5, 6, 2]. A magnitude of the ACMQ can be related to the instanton density in the QCD vacuum.

The exclusive vector meson electroproduction is a unique testing ground of the  $s$ -channel helicity properties of the quark-gluon coupling. Specifically,  $s$ -channel helicity non-conserving transitions from photons to vector mesons are possible even within the perturbative QCD for a fundamental reason that a helicity of mesons can be different from a sum of the quark and antiquark helicities (see [7] and references therein). The ACMQ would introduce an extra contribution to both the  $s$ -channel helicity conserving and non-conserving vector meson production amplitudes. Although it comes from manifestly soft region, a direct evaluation of such a contribution is needed.

Helicity properties of electroproduced vector mesons have been extensively studied in three experiments at HERA DESY, i.e. by the H1, ZEUS and HERMES collaborations. Although gross features of these data are well consistent with pQCD-based theoretical predictions (see review [7] and recent development in [8],[9]), there remain several open issues. An outstanding problem is a large relative phase of the leading helicity amplitudes for production of longitudinal and transverse  $\rho^0$ 's and  $\phi$ 's, which has been observed by the HERMES and H1 Collaborations [10, 11, 12]. It is definitely larger than the prediction based on the handbag mechanism [13] and also in the conventional pQCD pomeron-based color dipole approach [14] (see discussion in [7]). Besides that, pQCD-driven approaches seem to fail with the experimentally observed  $Q^2$  dependence of the ratio  $\sigma_L/\sigma_T$  in full experimentally studied range of  $Q^2$ : theoretical calculations substantially overestimate this ratio at large  $Q^2$ . Finally, it is important to evaluate an impact of new non-perturbative mechanism on the transition from real to virtual electroproduction.

In the present paper we study exclusive  $\rho$ - meson electroproduction off protons with allowance for the novel  $s$ -channel helicity non-conservation mechanism induced by the anomalous chromomagnetic moment of quarks. We focus on the simplest observables,  $\sigma_L$  and  $\sigma_T$ , a calculation of the full set of helicity amplitudes will be reported elsewhere.

## 2 Anomalous quark-gluon chromomagnetic interaction

In the most general case, the interaction vertex of massive quark with gluon can be written in the following form:

$$V_\mu(k_1^2, k_2^2, \kappa^2)t^a = -g_s t^a [F_1(k_1^2, k_2^2, \kappa^2)\gamma_\mu + \frac{\sigma_{\mu\nu}k_\nu}{2m}F_2(k_1^2, k_2^2, \kappa^2)], \quad (1)$$

where the first term is a conventional perturbative QCD quark-gluon vertex and the second term comes from non-perturbative sector of QCD. In Eq.1 the form factors  $F_{1,2}$  describe a nonlocality of the non-perturbative interaction,  $k_{1,2}$  are the momenta of incoming and outgoing quarks, respectively, and  $\kappa = k_2 - k_1$ ,  $m$  is the quark mass, and  $\sigma_{\mu\nu} = (\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)/2$ . In what follows, we focus on effects of the novel color chromomagnetic vertex and keep  $F_1(k_1^2, k_2^2, \kappa^2) = 1$ . The anomalous quark chromomagnetic moment (AQCM) equals

$$\mu_a = F_2(0, 0, 0).$$

In the earlier paper [4] it was shown that instantons, a strong vacuum fluctuations of gluon fields with nontrivial topology, generate an ACMQ which is proportional to the instanton density

$$\mu_a = -\pi^3 \int \frac{d\rho n(\rho)\rho^4}{\alpha_s(\rho)}.$$

In terms of the average size of instantons  $\rho_c$  and the dynamical quark mass  $m$  in non-perturbative QCD vacuum one finds [5]

$$\mu_a = -\frac{3\pi(m\rho_c)^2}{4\alpha_s(\rho_c)}, \quad (2)$$

which exhibits a strong sensitivity of the ACMQ to a dynamical mass of quarks. To this end we emphasize an implicit assumptions that quarks are light, ie., the above estimates of AQCM are valid for  $u, d, s$ , while for heavy quarks AQCM vanishes. For the average instanton size  $\rho_c^{-1} = 0.6$  GeV this mass is changing from  $m = 170$  MeV in the mean field (MF) approximation to  $m = 345$  MeV within Diakonov-Petrov (DP) model. The QCD strong coupling constant at the instanton scale can be evaluated as

$$\alpha_s(\rho_c) \approx 0.5,$$

and the resulting AQCM for light quarks is numerically quite large:

$$\mu_a^{MF} \approx -0.4, \quad \mu_a^{DP} \approx -1.6.$$

Recently, an AQCM of similar magnitude has been obtained within the Dyson-Schwinger equation approach to non-perturbative QCD (see discussion and references in [15]).

The form factor  $F_2(k_1^2, k_2^2, \kappa^2)$  suppresses the AQCM vertex at short distances when the respective virtualities are large. Within the instanton model its explicit is related to Fourier-transformed quark zero-mode and instanton fields and reads

$$F_2(k_1^2, k_2^2, \kappa^2) = \mu_a \Phi_q(|k_1| \rho/2) \Phi_q(|k_2| \rho/2) F_g(|\kappa| \rho),$$

where

$$\begin{aligned}\Phi_q(z) &= -z \frac{d}{dz} (I_0(z)K_0(z) - I_1(z)K_1(z)), \\ F_g(z) &= \frac{4}{z^2} - 2K_2(z)\end{aligned}$$

are the where  $I_\nu(z)$ ,  $K_\nu(z)$ , are the modified Bessel functions and  $\rho$  is the instanton size.

Recent discussion has shown [5] that the ACQM contribution complements the pQCD evaluations of the total quark-quark cross section in a way which improves constituent quark model description of high energy nucleon-nucleon total cross section. Furthermore, such model provide the soft contribution to the gluon distribution in the nucleon which is consistent with initial conditions to a DGLAP evolution of phenomenological PDFs. A purpose of the present communication is to explore the effects of ACQM in elastic (diffractive) electroproduction of  $\rho$  mesons.

### 3 Model for vector meson exclusive production

Driven by VBKL considerations, high energy diffractive production of vector mesons is usually described by an exchange of a color-singlet two-gluon tower in the  $t$ -channel. The corresponding diagrams are presented in Fig.1. By using the Sudakov expansion for the

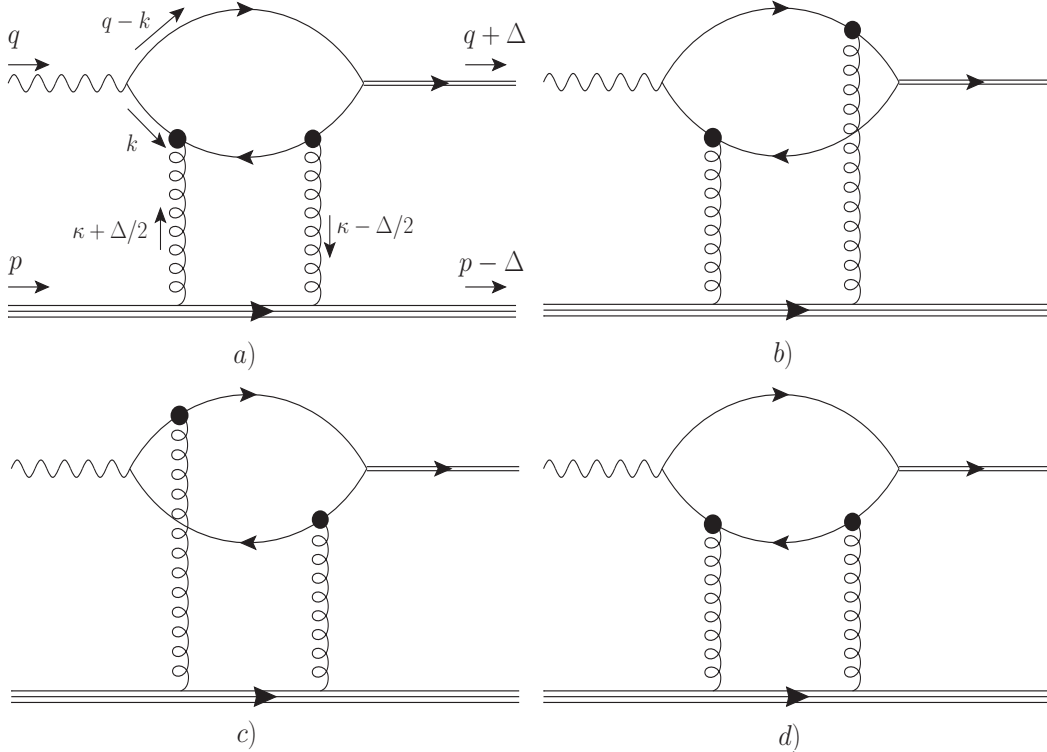


Figure 1: The diagrams which contribute to high energy exclusive vector meson electroproduction off proton by two gluon exchange. Here the blob stands for the generalized quark-gluon vertex Eq.1.

momenta of proton and virtual photon

$$p_\mu = p'_\mu + \frac{m_p^2}{s} q'_\mu, \quad q_\mu = q'_\mu - x p'_\mu, \quad q'^2 = p'^2 = 0, \quad (3)$$

where  $Q^2 = -q^2$ ,  $x = \frac{Q^2}{s} \ll 1$ ,  $s = 2(p'q')$ , the quark momentum  $k$  in the quark loop, gluon momentum  $\kappa$ , and momentum transfer to proton  $\Delta$  (see Fig.1) can be presented in the following form

$$\begin{aligned} k_\mu &= y p'_\mu + z q'_\mu + \vec{k}_\mu, \\ \kappa_\mu &= \alpha p'_\mu + \beta q'_\mu + \vec{\kappa}_\mu, \\ \Delta_\mu &= \delta p'_\mu + \sigma q'_\mu + \vec{\Delta}_\mu, \end{aligned} \quad (4)$$

where any vector  $\vec{l}$  is transversal part of four-vector  $l_\mu$  which satisfies the relation  $\vec{l} \cdot q' = \vec{l} \cdot p' = 0$ .

Hereafter we follow the  $k$ -factorization analysis developed in [16, 18, 17]. The polarization vectors for virtual photon  $e$  and vector meson  $V$  are

$$\begin{aligned} e_{T\mu} &= \vec{e}_\mu, \\ e_{L\mu} &= \frac{1}{Q}(q'_\mu + x p'_\mu), \\ V_{T\mu} &= \vec{V}_\mu + \frac{2(\vec{\Delta} \vec{V})}{s} p'_\mu, \\ V_{L\mu} &= \frac{1}{M} \left( q'_\mu + \frac{\vec{\Delta}^2 - M^2}{s} p'_\mu + \vec{\Delta}_\mu \right) \end{aligned} \quad (5)$$

where  $M$  is the mass of  $\bar{q}q$  pair on mass-shell:

$$M^2 = \frac{\vec{k}^2 + m^2}{z(1-z)} \quad (6)$$

The imaginary part of the amplitude takes the form

$$\begin{aligned} A(x, Q^2, \vec{\Delta}) &= -is \frac{c_V \sqrt{4\pi\alpha_{em}}}{4\pi^2} \int \frac{dz}{z(1-z)} \int d^2\vec{k} \psi(z, \vec{k}) \int \frac{d^2\vec{\kappa}}{\vec{\kappa}^4} \alpha_S \mathcal{F}(x, \vec{\kappa}, \vec{\Delta}) \times \\ &\times \left[ \frac{1-z}{z} \frac{I^{(a)}}{\vec{k}_{1a}^2 + m^2 + z(1-z)Q^2} + \frac{I^{(b)}}{\vec{k}_{1b}^2 + m^2 + z(1-z)Q^2} + \right. \\ &\left. + \frac{I^{(c)}}{\vec{k}_{1c}^2 + m^2 + z(1-z)Q^2} + \frac{z}{1-z} \frac{I^{(d)}}{\vec{k}_{1d}^2 + m^2 + z(1-z)Q^2} \right]. \end{aligned} \quad (7)$$

Here  $\alpha_{em}$  is the fine-structure constant,  $c_V = 1/\sqrt{2}$  is coming from the flavor part of the  $\rho$  meson wave function,  $\mathcal{F}(x, \vec{\kappa}, \vec{\Delta})$  is the differential gluon density and  $\psi(z, \vec{k})$  is light-cone wave function of the  $\rho$ -meson, for which we use a simple parameterization

$$\psi = c \exp\left(-\frac{a^2 \mathbf{p}^2}{2}\right) = c \exp\left(-\frac{a^2}{2} \left(\vec{k}^2 + \frac{1}{4}(2z-1)^2 M^2\right)\right) \quad (8)$$

where  $\mathbf{p}$  is 3-dimensional relative momentum of quarks in pair. Two constants  $a$  and  $c$  were fixed by the normalization of wave function and decay width  $\Gamma(\rho \rightarrow e^+e^-)$ , we find  $a = 3.927 \text{ GeV}^{-1}$ ,  $c = 17.44$ .

For the QCD running coupling we use

$$\alpha_s(q^2) = \frac{4\pi}{9 \ln((q^2 + m_g^2)/\Lambda_{QCD}^2)}, \quad (9)$$

where  $\Lambda_{QCD} = 0.28 \text{ GeV}$  and the value  $m_g = 0.88 \text{ GeV}$  imposes the infrared freezing at  $\alpha_s(1/\rho_c^2) \approx \pi/6$  [2]. Here  $q^2$  is the maximum virtuality of momentum which inserted to vertex, i.e.  $q^2 = \text{Max}(k_1^2, k_2^2, \kappa^2)$ .

$I^{(i)}$  is the trace over quark line in  $i$ ) diagram from Fig.1 divided by  $2s^2$ . It is involved a three parts:

$$I^{(i)} = I_{pert}^{(i)} + I_{cm}^{(i)} + I_{mix}^{(i)}. \quad (10)$$

Below we are using the following notation for the transverse momentum of quark

$$\begin{aligned} \vec{k}_{1a} &= \vec{k} - (1-z)\vec{\Delta} \\ \vec{k}_{1b} &= \vec{k} - (1-z)\vec{\Delta} + \vec{\kappa} + \frac{1}{2}\vec{\Delta} \\ \vec{k}_{1c} &= \vec{k} - (1-z)\vec{\Delta} - \vec{\kappa} + \frac{1}{2}\vec{\Delta} \\ \vec{k}_{1d} &= \vec{k} + z\vec{\Delta} \end{aligned} \quad (11)$$

Such shift of momentum is needed for keeping transverse momentum of quarks inserted to meson vertex to be equal  $\vec{k}$  for all diagrams in order to take out  $\psi(z, \vec{k})$  as common multiplier. Besides,  $[\vec{a}\vec{b}] = a_x b_y - a_y b_x$ .

The formula for  $TT$  transition in case when both of quark-gluon vertices are perturbative is

$$I_{pert}^{(c)}(T \rightarrow T) = \left[ (\vec{e}\vec{V}^*)(m^2 + \vec{k}\vec{k}_{1c}) + (\vec{V}^*\vec{k})(\vec{e}\vec{k}_{1c})(1-2z)^2 - (\vec{e}\vec{k})(\vec{V}^*\vec{k}_{1c}) \right]. \quad (12)$$

For pure perturbative vertices there is the relation between different contributions

$$I_{pert}^{(b)} = I_{pert}^{(c)} = -\frac{1-z}{z} I_{pert}^{(a)} = -\frac{z}{1-z} I_{pert}^{(d)}$$

subject to a proper substitution of the loop quark momenta the relevant diagrams of Fig.1.

When both quark-gluon vertices come from nonperturbative ACQM, we find

$$\begin{aligned} I_{cm}^{(a)}(T \rightarrow T) &= -\frac{z}{1-z} \left[ (\vec{e}\vec{V}^*)(m^2 + \vec{k}\vec{k}_{1a}) + (\vec{V}^*\vec{k})(\vec{e}\vec{k}_{1a})(1-2z)^2 - (\vec{e}\vec{k})(\vec{V}^*\vec{k}_{1a}) \right] \vec{\kappa}^2 \times \\ &\times F_2(k_{I \text{ avg}}^2, 0, \kappa^2) F_2(k_{II \text{ avg}}^2, 0, \kappa^2). \end{aligned} \quad (13)$$

Here we notice that one of quarks is always on mass-shell, and  $k_{I, II \text{ avg}}^2$  stand for the virtuality of the off-mass shell quark. To obtain formula for  $I_{cm}^{(d)}$  one should perform the substitutions  $z/(1-z) \rightarrow (1-z)/z$  and  $\vec{k}_{1a} \rightarrow \vec{k}_{1d}$  in above expression. The AQCM contribution from graph in Fig.1c is

$$\begin{aligned} I_{cm}^{(c)}(T \rightarrow T) &= \left[ ((1-2z)^2(\vec{V}^*\vec{k})(\vec{k}_{1c}\vec{e}) - (\vec{k}\vec{k}_{1c})(\vec{e}\vec{V}^*) + (\vec{k}\vec{e})(\vec{V}^*\vec{k}_{1c}))\vec{\kappa}^2 + \right. \\ &\left. + m^2(2(\vec{e}\vec{\kappa})(\vec{V}^*\vec{\kappa}) - (\vec{e}\vec{V}^*)\vec{\kappa}^2) \right] F_2(k_{I \text{ avg}}^2, 0, \kappa^2) F_2(k_{II \text{ avg}}^2, 0, \kappa^2). \end{aligned} \quad (14)$$

The replacement  $\vec{k}_{1c} \rightarrow \vec{k}_{1b}$  leads to the formula for  $I_{cm}^{(b)}$ .

The interference of the pQCD and ACQM vertices gives

$$I_{mix}^{(c)}(T \rightarrow T) = m \left[ (\vec{V}^* \vec{k})(\vec{\kappa} \vec{e})(1 - 2z) - [\vec{e} \vec{\kappa}][\vec{V}^* \vec{k}] - (\vec{e} \vec{k}_{1c})(\vec{\kappa} \vec{V})(1 - 2z) - [\vec{e} \vec{k}_{1c}][\vec{\kappa} \vec{V}^*] \right] \times \\ \times (F_2(k_{II \text{ avg}}^2, 0, \kappa^2) - F_2(k_{I \text{ avg}}^2, 0, \kappa^2)) \quad (15)$$

The  $I_{mix}^{(b)}$  is obtained from the above by substitution  $k_{1c} \rightarrow k_{1b}$ . The remaining amplitudes are

$$I_{mix}^{(a)}(T \rightarrow T) = \frac{zm}{1-z} \left[ (\vec{V}^* \vec{k})(\vec{\kappa} \vec{e})(1 - 2z) - [\vec{e} \vec{\kappa}][\vec{V}^* \vec{k}] - (\vec{e} \vec{k}_{1a})(\vec{\kappa} \vec{V})(1 - 2z) - [\vec{e} \vec{k}_{1a}][\vec{\kappa} \vec{V}^*] \right] \times \\ \times (F_2(k_{II \text{ avg}}^2, 0, \kappa^2) - F_2(k_{I \text{ avg}}^2, 0, \kappa^2)) \quad (16)$$

$$I_{mix}^{(d)}(T \rightarrow T) = \frac{(1-z)m}{z} \left[ (\vec{V}^* \vec{k})(\vec{\kappa} \vec{e})(1 - 2z) + [\vec{e} \vec{\kappa}][\vec{V}^* \vec{k}] - (\vec{e} \vec{k}_{1d})(\vec{\kappa} \vec{V}^*)(1 - 2z) + [\vec{e} \vec{k}_{1d}][\vec{\kappa} \vec{V}^*] \right] \times \\ \times (F_2(k_{II \text{ avg}}^2, 0, \kappa^2) - F_2(k_{I \text{ avg}}^2, 0, \kappa^2)) \quad (17)$$

For the longitudinal polarization we obtain

$$I_{pert}^{(c)}(L \rightarrow L) = -4QMz^2(1-z)^2 \\ I_{cm}^{(c)}(L \rightarrow L) = -4QMz^2(1-z)^2 \vec{\kappa}^2 F_2(k_{I \text{ avg}}^2, 0, \kappa^2) F_2(k_{II \text{ avg}}^2, 0, \kappa^2). \quad (18)$$

And  $I^{(b)} = I^{(c)} = -\frac{1-z}{z} I^{(a)} = -\frac{z}{1-z} I^{(d)}$  with corresponding  $\vec{k}_{1i}$ . In the longitudinal case the contribution from the interference of pQCD and AQCM vertices vanishes

$$I_{mix}^{(a)}(L \rightarrow L) = I_{mix}^{(b)} = I_{mix}^{(c)} = I_{mix}^{(d)} = 0. \quad (19)$$

A common feature of nonperturbative approaches is a fast running dynamical mass of constituent quarks which drops to a small current quark mass at large virtualities. In principle, the running of the quark masses affect the  $Q^2$  dependence of vector meson production observables. However, such an ill-fledged involved calculation is beyond the scope of the present communication. Here we only recall that according to the color transparency considerations the vector meson production amplitudes are dominated by the components of the vector meson wave function taken at transverse size, i.e., the scanning radius  $r_S \sim 6/\sqrt{Q^2 + m_V^2}$  [19, 20, 7]. Consequently, the virtuality of quarks is  $\propto (Q^2 + m_V^2)$ , and arguably one can model an approach to the pQCD regime at large virtuality of the photon making use of a simple approximation

$$m(Q^2) = \frac{m(0)}{1 + Q^2/m_V^2}, \quad (20)$$

where  $m(0) = 345$  MeV and  $m_V = 770$  MeV

## 4 Discussion of the results for $\sigma_L$ and $\sigma_T$

The final result for cross sections is presented in Fig.2 in comparison with data obtained by H1 and ZEUS Collaborations. Helicity flip transitions are found to give a very small contribution to the total production cross section, see also discussion in [7]:

$$\begin{aligned}\sigma_T &= \sigma_{T \rightarrow T} + \sigma_{T \rightarrow L} \approx \sigma_{T \rightarrow T} \\ \sigma_L &= \sigma_{L \rightarrow L} + \sigma_{L \rightarrow T} \approx \sigma_{L \rightarrow L}.\end{aligned}\tag{21}$$

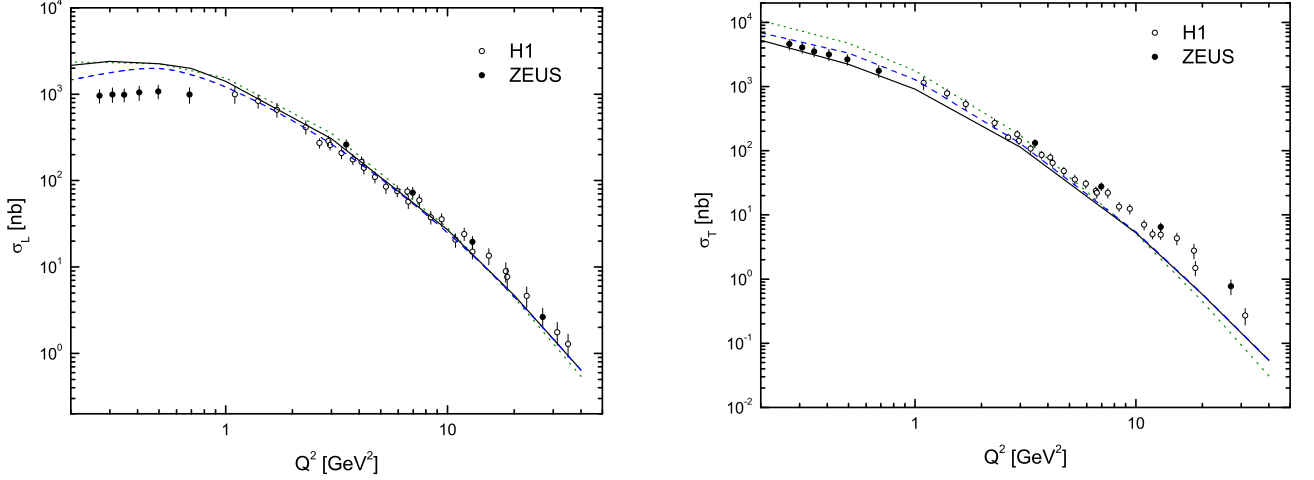


Figure 2: Cross sections of  $\rho$  meson exclusive electroproduction: left panel is for longitudinal virtual photon polarization and right panel for transversal photon polarization. The solid line is the calculation with AQCM, dashed line is the result of pQCD contribution with running quark mass, Eq.20, and dotted line is pQCD calculation with fixed quark mass  $m_q = 220$  MeV [17, 18]. Experimental points are taken from [21] for H1 and from [22] for ZEUS Collaborations.

The longitudinal cross-section  $\sigma_L$  is free of the interference of the pQCD and AQCM vertices. Allowance for AQCM effects slightly enhances  $\sigma_L$  in the region of non-perturbative small  $Q^2$ , but still the cross section is overestimated in low  $Q^2$  region. There is one caveat, though: we evaluated the pQCD contribution using the unintegrated gluon density which has been tuned to the experimental data on the proton structure function. To be more accurate, one must reanalyze the structure function data with allowance for the AQCM effect, arguably that would lower somewhat the resulting pQCD contribution to  $\sigma_L$  bringing the theoretical curve closer to the experimental data points.

The case of the transverse cross section  $\sigma_T$  is more subtle. In this case the effect of the pQCD-AQCM interference is quite substantial. As a matter of fact, the resulting destructive interference numerically takes over the pure AQCM contribution and lowers  $\sigma_T$  compared to the pure pQCD contribution. It is well understood that  $\sigma_T$  is more susceptible to the non-perturbative effects in comparison with  $\sigma_L$ . Indeed, the non-perturbative corrections to  $\sigma_T$  die out substantially slower than corrections to  $\sigma_L$ .



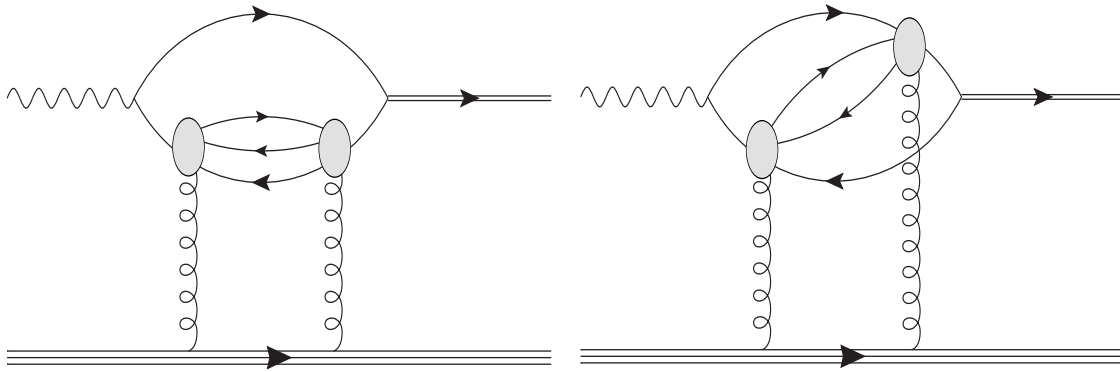


Figure 3: Additional contribution to exclusive electroproduction of the  $\rho$  meson coming from quark-antiquark exchange between chromomagnetic vertices.

To this end we notice that we only treated a leading in  $1/N_c$  restricted class of the instanton induced non-perturbative QCD interactions which are reducible to the anomalous chromomagnetic quark-gluon vertex. The full-fledged t'Hooft's-like multipartonic interaction [3] gives rise to a more complicated diagrams, examples are shown in Fig.3. The issue of such contributions will be considered elsewhere [23]. We also have checked the possible effect of introduction of the form factor into pQCD vertex which cuts low transfer momentum region where one-gluon exchange picture looks questionable. It leads to the decreasing of the both longitudinal and transverse cross sections at low  $Q^2$ . In this case we observe significant improvement of agreement with experiment of our calculation for  $\sigma_L$ , but agreement of calculated  $\sigma_T$  with data becomes worse.

As we emphasized, the ACQM vertex manifestly violates the quark  $s$ -channel helicity conservation. Arguably, the effects of ACQM will be stronger in the helicity flip amplitudes of vector meson electroproduction. The numerical results for full spin density matrix of diffractive  $\rho$ -mesons will be presented elsewhere.

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## References

- [1] T. Schäfer and E.V. Shuryak, Rev. Mod. Phys. **70** (1998) 1323.
- [2] D. Diakonov, Prog. Par. Nucl. Phys. **51** (2003) 173.
- [3] G.t Hooft, Phys. Rev. **D32** (1976) 3432.
- [4] N. I. Kochelev, Phys. Lett. **B426** (1998) 149.
- [5] N. Kochelev, Phys. Part. Nucl. Lett. **7** (2010) 326. [arXiv:0907.3555 [hep-ph]].
- [6] N. I. Kochelev, hep-ph/9707418.

- [7] I. P. Ivanov, N. N. Nikolaev and A. A. Savin, Phys. Part. Nucl. **37** (2006) 1.
- [8] I. V. Anikin, A. Besse, D. Y. Ivanov, B. Pire, L. Szymanowski, S. Wallon, Phys. Rev. **D84** (2011) 054004. [arXiv:1105.1761 [hep-ph]].
- [9] I. V. Anikin, D. Y. Ivanov, B. Pire, L. Szymanowski, S. Wallon, Nucl. Phys. **B828** (2010) 1. [arXiv:0909.4090 [hep-ph]].
- [10] A. Airapetian *et al.* [HERMES Collaboration], Eur. Phys. J. **C62** (2009) 659. [arXiv:0901.0701 [hep-ex]].
- [11] W. Augustyniak, A. Borissov and S. I. Manayenkov, arXiv:0808.0669 [hep-ex].
- [12] C. Adloff *et al.* [H1 Collaboration], Eur. Phys. J. **C13** (2000) 371.
- [13] S. V. Goloskokov and P. Kroll, Eur. Phys. J. **C53** (2008) 367.
- [14] J. Nemchik, N. N. Nikolaev, E. Predazzi and B. G. Zakharov, Z. Phys. **C75** (1997) 71.
- [15] L. Chang, C. D. Roberts, P. C. Tandy, [arXiv:1107.4003 [nucl-th]].
- [16] E. V. Kuraev, N. N. Nikolaev, B. G. Zakharov, JETP Lett. **68** (1998) 696-703. [hep-ph/9809539].
- [17] I. P. Ivanov, N. N. Nikolaev, Phys. Atom. Nucl. **64** (2001) 753; Phys. Rev. **D65** (2002) 054004.
- [18] I. P. Ivanov, [hep-ph/0303053].
- [19] N. N. Nikolaev, Comments Nucl. Part. Phys. **21** (1992) 41.
- [20] B. G. Kopeliovich *et al.* Phys. Lett. **B309** (1993) 179.
- [21] F. D. Aaron *et al.* [ H1 Collaboration ], JHEP **1005** (2010) 032. [arXiv:0910.5831 [hep-ex]].
- [22] B. Clerbaux, arXiv:hep-ph/9908519.
- [23] N. Korchagin, N. Kochelev, N. Nikolaev, paper in preparation.